TIDAL SIMULATION USING REGIONAL OCEAN MODELING SYSTEM (ROMS)

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ABSTRACT

A three dimensional general circulation model is used to simulate tides along the central western coast of U.S. The model, which is configured from the Regional Ocean Modeling System (ROMS), is three-level nested with the finest resolution of 1.6 km in the Monterey Bay, California. Forced by tidal signal along the open boundaries in west, north and south directions, ROMS can simulate barotropic tides reasonably well in the region. The total discrepancy of the amplitudes of eight major tide constituents, as measured by root of summed squares, is 3.5 cm in the open ocean compared with tide amplitudes estimated by Topex/POSEIDON along-track altimetry observation. Along the coastal region, the discrepancy of amplitudes is 5.4 cm which is about 10% of the amplitude of the most energetic M_2 constituent. For these major tide constituents, the phase error is generally much less than half hour. The simulated sea surface tidal current, which is heavily influenced by internal tide activity, shows sensitivity to the stratification of the model and has large room to improve.

1. INTRODUCTION

The presence of tidal signal poses a major challenge for the development of coastal operational forecasting systems. The barotropic tide signal associated with sea surface height is relatively straightforward to predict and simulate. However, the interaction of barotropic tides and topography would generate internal tides and make the flow pattern very complex with the presence of time-dependent stratification and mean current. Another motivation to develop a tidal-permitting circulation model is that the temperature, salinity and current collected by moving platforms (e.g., gliders or AUVs) contain both the circulation and tidal signals. To assimilate these data into a non-tidal-permitting model will introduce large errors in the model. For many applications of a coastal operational forecasting system, it is certainly desirable to simulate tide directly instead of providing a detided solution.

A three level nested model is configured for the Monterey Bay, California to simulate tide. The oceanic general circulation model used is the Regional Ocean Modeling System (ROMS), which is a community model designed for coastal applications [1].

The purpose of our research is to test the capability of ROMS in simulating tides. The research also serves as a necessary exercise to implement tides in an operational ocean forecasting system. In this paper, we emphasize the validation of the model tide simulation. The characteristics and energetics of tides of the region will be reported in separate publications.

The paper is organized as following. After the brief Introduction, Section 2 discusses the model we use. Section 3 validates tidal simulation using tidal parameters from satellite altimetry observation and tide gauges. Section 4 presents the sea surface tidal current simulation and its comparison with high frequency coast radar observation. Section 5 summarizes our research.

2. MODEL CONFIGURATION AND TIDAL FORCING

The model used is three-level nested (Fig. 1). The outmost model domain which has the coarsest-resolution (L0 model) covers the U.S. western coastal region from southern California to Oregon, and level 1 model (L1 model) covers the central and northern California coast and level 2 model (L2 model) zooms in for the Monterey Bay region. The nesting of the model is realized through the Adaptive Grid Refinement in Fortran (AGRIF) package which is based on the use of pointers [2]. The package is systematically tested in [3]. The testing indicates that the package can provide a continuous solution at the interface of coarse and fine model grid. Table 1 lists the domains and details of our nested model. The horizontal

Table 1. The maximum and minimum depths, horizontal range in latitudes and longitudes, resolutions, and time steps of the three-level nested ROMS model for U.S. western coast.

	Max Depth	Min Depth(m)	Latitude(N)	Longitude(W)	Resolution(km)	Time Step(s)
L0 Model	5346.5	285.0	24.0 47.9	139.5 115.6	15.7	900
L1 Model	4780.8	100.0	32.9 41.7	129.0 120.0	5.0	300
L2 Model	3943.9	10.2	35.1 37.8	123.6 121.1	1.6	100

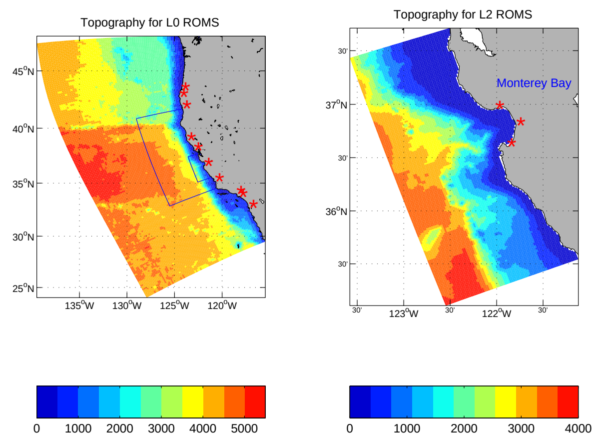

Figure 1. Topography in the coarsest-resolution model domain (L0, left), and the topography in the finest-resolution model domain (L2, right) of the three-level nested model. The boundaries of the nested models are also shown in left panel. The red stars show the tide gauges used to validate model tidal solution. There are 10 gauges for L0 model and three gauges for L2 model.

resolution for L2 model is 1.6 km and there are 32 vertical levels following the bottom topography. Open boundary conditions [4] are used along its western, southern and northern boundaries. Flather boundary condition [5] is used on L0 model to allow the propagation of tide signal into the model domain. The detailed boundary conditions for the barotropic velocity and sea surface height are shown in Table 2. Using 16 cpus on SGI altix 3000 computer, it takes one minute wall-clock time to integrate model for one hour.

The basic feature of the Monterey Bay region is a submarine canyon cutting into the bay in southwest and northeast direction. In reality (Fig. 5), the canyon width (as measured by 200 m depth line) shrinks from 15 km at the shelf break to 2 km at the canyon head. This unique feature enhances the internal tide activity in the region [6] and also makes the Monterey Bay one of the most studied region of U.S. west coast. Our model uses a smoothed version of Smith and Sandwell bathymetry [7] and can not fully represent the complex features of the submarine canyon (Fig. 6).

In the present research, our focus is the tides around the Monterey Bay. The earth tide, load tide and

Table 2. Boundary conditions used for sea surface height and barotropic velocity for the three-level nested ROMS model of U.S. western coast.

	Open Boundary	Closed Boundary
Sea Surface Height	Chapman	Zero Gradient
Tangential Velocity	Oblique Radiation	Free Slip
Normal Velocity	Flather Condition	Zero

astronomical tide generating potential have been neglected since the influence of these factors are minor in regional tide simulations [8]. The tide forcing is from a global inverse barotropic tide model (TPXO.6) [9], which has a horizontal resolution of 0.25 degrees and uses the inverse modeling technique to assimilate satellite altimetry cross-over observation. Eight major tide constituents of diurnal and semidiurnal frequencies ($M_2, K_1, O_1, S_2, N_2, P_1, K_2, Q_1$, ordered by their amplitudes in the region) are used for our boundary condition. The simulation period is August 2003 which is the field experiment of Adaptive Ocean Sampling Network. During this field experiment, a detided version of the model is used to conduct experimental coastal ocean operational forecasting. The atmospheric forcing is wind stress, heat flux and freshwater flux from COAMPS [10]. The model is integrated for one month then the tide parameters are estimated to compare with observations. Our analysis shows that for sea surface height, the tidal amplitude and phase estimation with one month model output and those with one year model output is roughly the same. The T_TIDE matlab package [11] is used for the tidal analysis. The package is the matlab version of tidal harmonic analysis software in Fortran [12].

3. VALIDATION OF BAROTROPIC TIDES

Fig. 2 compares the amplitude of the most energetic M_2 constituent from L0 model and Topex/POSEIDON along-track altimetry observation. Left panel of Fig. 2 shows the satellite altimetry M_2 amplitude at model grid points. Totally there are 1137 data points that are within 6 km of model gird points. The amplitude of M_2 tide increases from less than 10 cm in a amphidrome around 30° N, 130° W to around 100 cm around the northeast corner of the model domain. The feature is reproduced

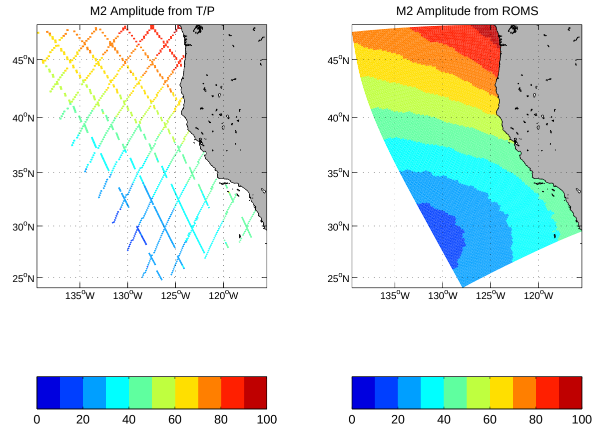

Figure 2. The sea surface height amplitude for M_2 constituent from Topex/POSEIDON along-track altimetry observation (left) and from model (right). The units are cm.

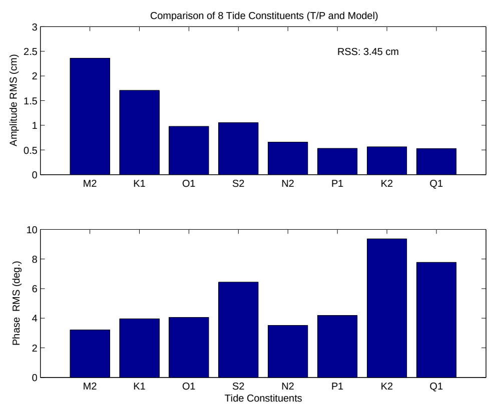

Figure 3. The root-mean-square discrepancy for tidal amplitude (upper) and phase (lower) from Topex/POSEIDON along-track altimetry observation and model.

very well by our model (right panel of Fig. 2). The phase gradually increases from south to north and shows a propagation along the coast (figure ignored).

The root-mean-square (RMS) discrepancy between model and satellite sea surface height amplitude is less than 2.5 cm for M_2 constituent and less than 0.5 cm for Q_1 constituent (upper panel of Fig. 3). The root of summed squares (RSS) is 3.5 cm for the amplitudes of the eight constituents. The RMS discrepancy for phase is generally less than 10 degrees (lower panel of Fig. 3). For M_2 constituent, the phase discrepancy is less than 3 degrees, which is equivalent to 6 minutes. The nested model simulates tide very accurately with the presence of wind stress and heat flux forcing.

For the coastal region, the upper panel of Fig. 4 compares the amplitude of model to 10 tide gauges in L0 model domain. These 10 tide gauges are distributed along U.S. west coast from southern California to Oregon (Red stars in left panel of Fig. 1). The RMS discrepancy for

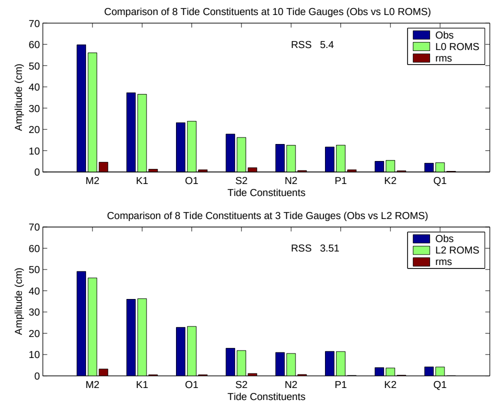

Figure 4. The root-mean-square discrepancy for tidal amplitudes for 10 tide gauges in L0 model (red bars in the upper panel) and 3 tide gauges in L2 model (red bars in the lower panel). The mean amplitudes of tide gauges and of relevant model grid points are shown in blue and green bars respectively.

amplitude decreases from 4.6 cm for M_2 to 0.3 cm for Q1 constituent. The RSS of amplitude is 5.4 cm. Along the coast region, the discrepancy for amplitude becomes larger than that in open ocean because of coarse resolution of the model, the unsatisfactory representation of bathymetry, and the error in boundary conditions. For L2 model which has a resolution of 1.6 km, the RSS discrepancy for amplitudes is reduced to 3.5 cm for Monterey Bay region (lower panel of Fig. 4). The phase discrepancy between model and tide gauges is generally less than 8 degrees (figure ignored).

4. COMPARISON WITH COASTAL RADAR OBSERVATION

Observations indicate that the Monterey Bay submarine canyon is associated with enhanced internal tide activity [6]. The internal tide current amplitude could reach 15-20 cm/s and shows significant horizontal variation. The analysis of high-frequency radar observation indicates significant and robust internal tide signal in surface current [13]. Thus model surface current is compared with radar sea surface current observation for August 2003. Fig. 5 shows the sea surface tidal current ellipses for the M_2 constituent from radar observation. The major features include, 1) the amplitude of tide current is greatly enhanced for the shelf region where the water depth is less than 200 m, 2) associated with the submarine canyon, the rotation of tide current is counterclockwise. Based on the theory of internal tide generation [14], the generation of internal tides relies on the interaction of barotropic tide and bottom topographic features. Stratification also plays an important role in the process.

In order to analyze the sensitivity of surface tide current simulation to stratification, a group of experiments were conducted (Table 3 and Fig. 6). In these experiments, the

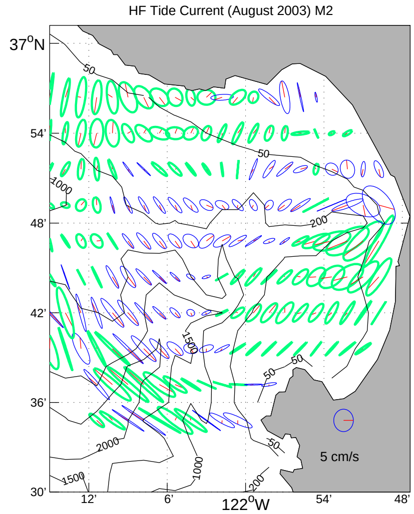

Figure 5. The sea surface tidal current ellipses for M_2 from high-frequency coastal radar observation for August 2003. The tidal current ellipse shows the length of major axis, the length of minor axis, the inclination from due east. The red line in current ellipse shows the direction of tidal current when the sea surface height reaches the maximum at Moss Landing station of Monterey Bay. The contours show the selected (50, 200, 1000, 1500, 2000m) isobathymetric lines.

fundamental difference is stratification. In Experiment 1, the model is integrated starting from Levitus climatology [15] [16] as the initial condition. In Experiment 2, the final state of one-year spin-up run starting from Levitus climatology is used as initial condition. In Experiments 3 and 4, the model starts from a data-assimilated initial condition for August 2003. Comparison shows that the temperature and salinity profile is very close to observation for monthly average with the difference of temperature less than 0.5 degree, and the difference of salinity less than 0.2 psu (figure ignored). The difference of Experiments 4 and 3 is that the monthly wind stress forcing is used in Experiment 4, while for Experiment 3 the hourly wind stress forcing is used. From Experiment 1 to Experiment 4, the barotropic tide signal associated with sea surface height does not change much as expected. The surface tide current simulation, however, is gradually improved with enhanced surface tide current in shelf region and the appearing of counterclockwise tide current rotation associated with model submarine canyon. The improvement of surface tidal current is also obvious in the length of major axis and RMS discrepancy of the length of the major axis from model and from high-frequency radar observation. The observed length of major axis is 5.8 cm/s. The length of major axis from model is gradually increased from 2.07 cm/s for Experiment 1 to 4.24 cm/s for Experiment 4, presumably by better representation of stratification for the whole model domain. The RMS discrepancy of the length of major axis between the observation and model decreases from 4.48 cm/s for Experiment 1 to 2.76 cm/s for Experiment 4. Thus for a given representation of bottom topography, the internal

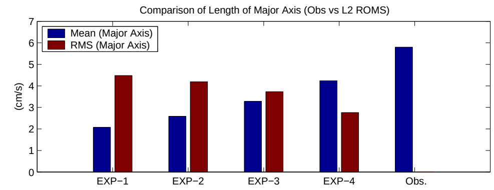

Figure 7. The root-mean-square discrepancy of the length of major axis between model and high-frequency coastal radar observation (red), and the mean of the length of major axis (blue). The mean of the length of major axis from observation is also shown. The four experiments are defined as in Fig. 6.

tide simulation could be improved with better representation of stratification. The implication of this results needs to be explored further in future work.

5. CONCLUSION

A three dimensional, three-level nested general circulation model is used to simulate tides along the central western coast of U.S. The outermost model domain covers the U.S. west coast region from Southern California to Oregon, and the innermost domain zooms in for Monterey Bay, California, with a horizontal resolution of 1.6 km and 32 levels in vertical direction. The model can simulate barotropic tidal signal very well in the region. The total discrepancy of the amplitudes of the eight major tide constituents, measured by root of summed squares (RSS), is 3.5 cm in the open ocean. For these major tide constituents, the phase error is generally much less than 10 degrees. Along the coastal region, the comparison with 10 tide gauges shows that the RSS of amplitudes is 5.4 cm which is about 10% of the amplitude of the most energetic M_2 constituent. In the innermost model domain of Monterey Bay, the RSS of amplitudes is 3.5 cm. The general feature of surface tide current, which reveals the internal tide activity of the region, can be reproduced by the model. However, there is large room for improvement in terms of magnitude and spatial pattern of surface tidal current. The innermost model domain has a relatively coarse resolution in both horizontal and vertical direction and model topography is also too smooth to simulate the generating processes of internal tides. These aspects will be improved in the next generation ROMS we are developing. The addition of tide signal in the three-level nested regional general circulation model is a significant step toward an tide-permitting forecasting system of the Monterey Bay region.

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Table 3. Numerical experiments to analyze the sensitivity of surface tide current to stratification. The first row is the model initial condition. The second row is the model forcing. The third row is the mean of the length of major axises of surface tide current for M_2 constituent. The fourth row is the root-mean-square discrepancy of the length of major axises between the model and high-frequency coastal radar observation (shown in column 6).

	EXP 1	EXP 2	EXP 3	EXP 4	HF Radar
Initial Condition	Levitus climatology	1-year spin-up from Levitus	Data-assimilated	Data-assimilated	
Forcing	hourly forcing	hourly forcing	hourly forcing	monthly forcing	
Mean of Major Axises (cm/s)	2.07	2.59	3.28	4.24	5.80
RMS of Major Axises (cm/s)	4.48	4.19	3.73	2.76	

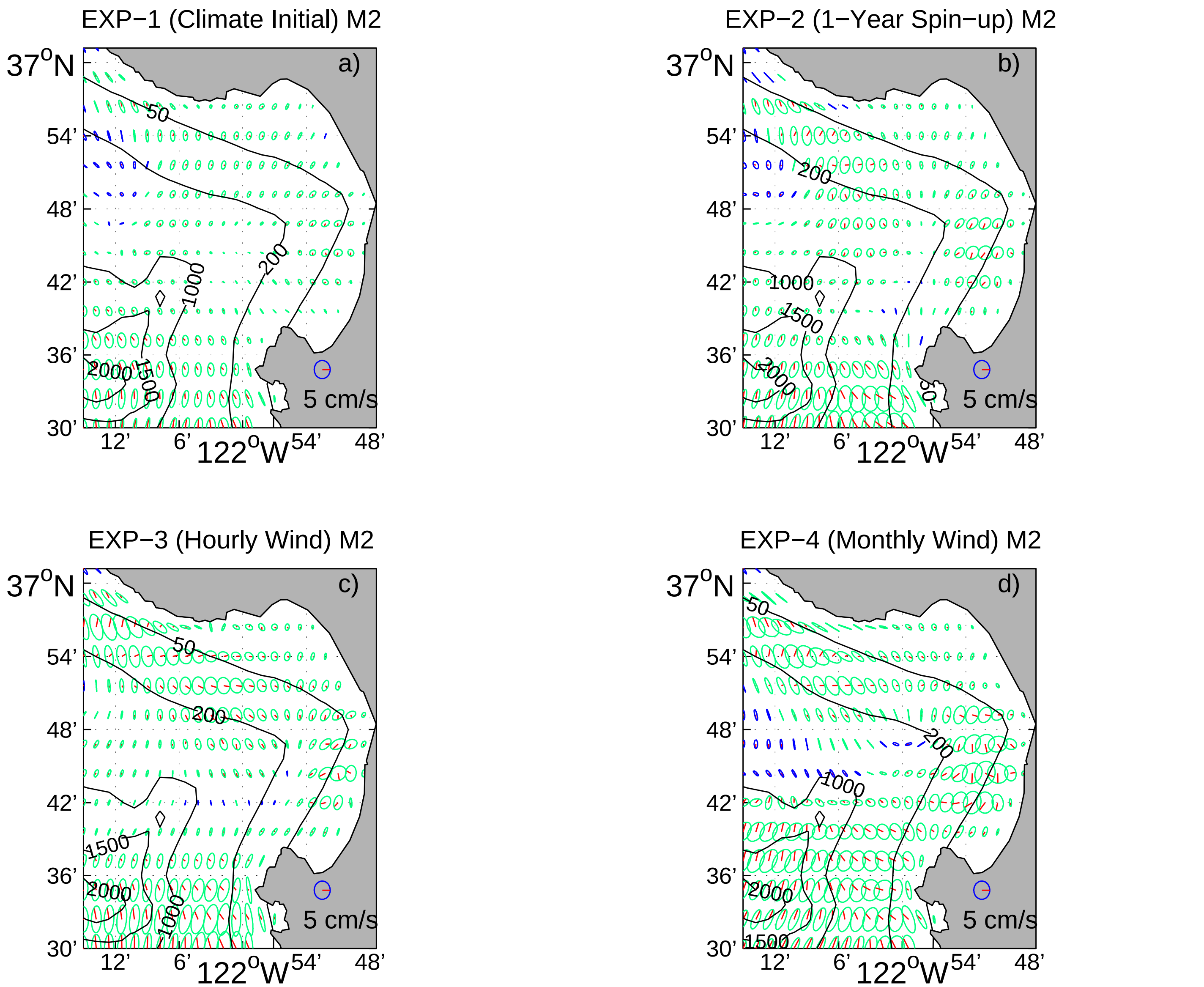

Figure 6. The sea surface tidal current ellipses for M_2 constituent from model runs with different stratifications. Experiment 1 starts from Levitus climatology. Experiment 2 starts from 1-year spin-up run from Levitus climatology. Experiment 3 starts from data-assimilated initial condition of August 2003 with hourly wind stress forcing. Experiment 4 starts from the same initial condition as Experiment 3 except with monthly wind stress forcing. The contours show the selected (50, 200, 1000, 1500, 2000m) model isobathymetric lines.

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